WDM Target Experiments on NDCX-I and NDCX-II

Presented by
Frank Bieniosek (LBNL)
for the HIFS-VNL (LBNL, LLNL, PPPL)

2010 Ion Beam Driven High Energy Density Workshop

Pleasanton, CA
June 22 – June 24, 2010

This work was performed under the auspices of the U.S. Department of Energy by LLNL under contract DE-AC52-07NA27344, the University of California, LBNL under Contract Number DE-AC02-05CH1123 and PPPL under contract DEFG0295ER40919 .

Overview of HIFS-VNL target experiment program

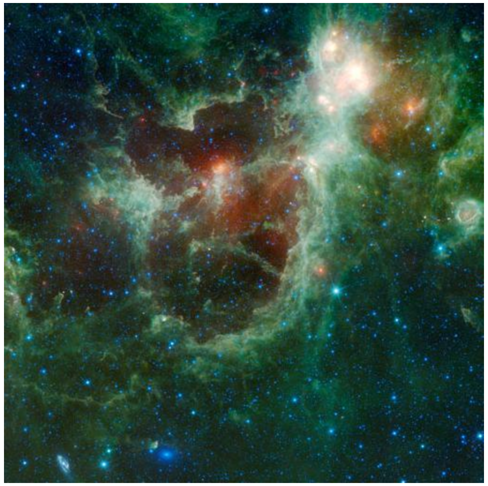
- This workshop continues a series of workshops on ion beam driven HEDP.
  - -Accelerator Driven High Energy Density Physics Oct. 26-29, 2004 http://hifweb.lbl.gov/public/hedpworkshop/toc.html
  - -Workshop on Accelerator Driven Warm Dense Matter Physics Feb 22-24, 2006, https://ilsa.llnl.gov/html/conferences/past/wdm_2006/index.html
  - - WDM School Jan. 10-16, 2008 http://hifweb.lbl.gov/wdmschool/

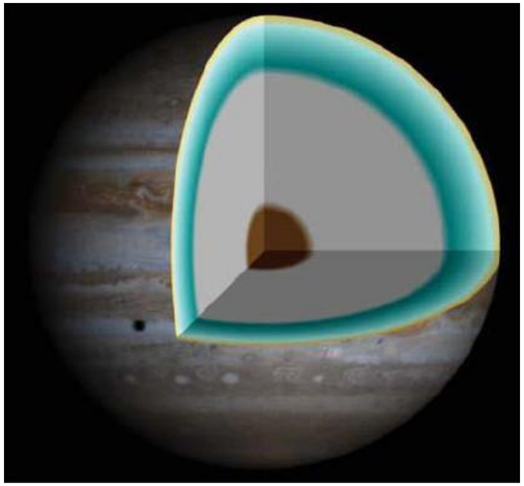
- Explore opportunities and capabilities for NDCX-I and II ion beam driven user facility. NDCX-II to be available for first target experiments after beam commissioning, ~ late 2012.

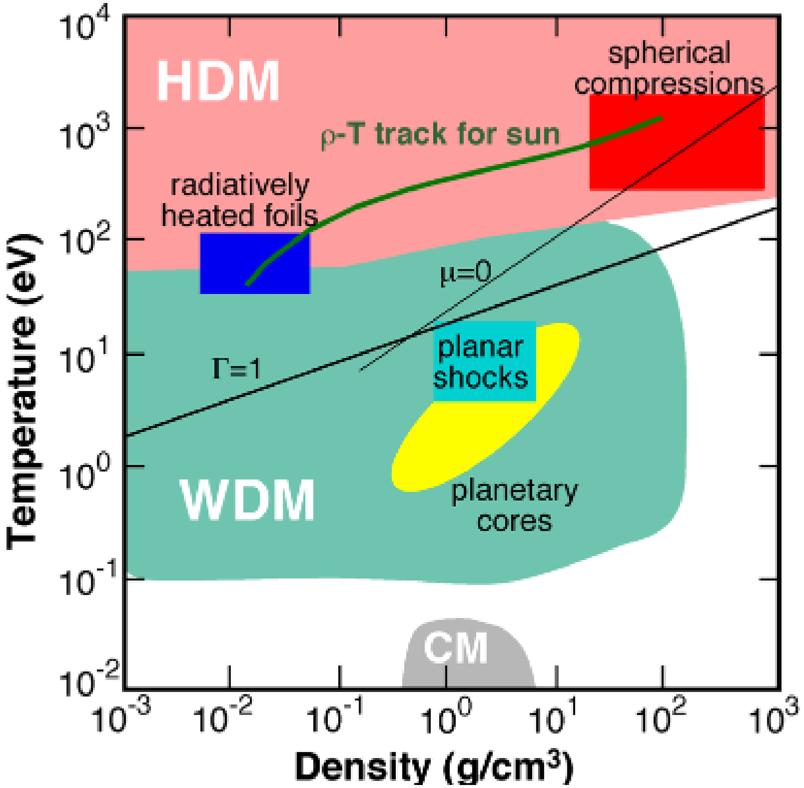
- New target chamber with enhanced capability for diagnostics to be designed for installation on NDCX-II; *e.g.* high power lasers, cryo-targets, x-ray diagnostics.

- This presentation focuses on target chamber HEDP experiments in NDCX-I and NDCX-II. Target diagnostics will be discussed by Pavel Ni.

Understanding the nature of high energy density matter enhances our understanding of the universe and enables important applications.







Astrophysics

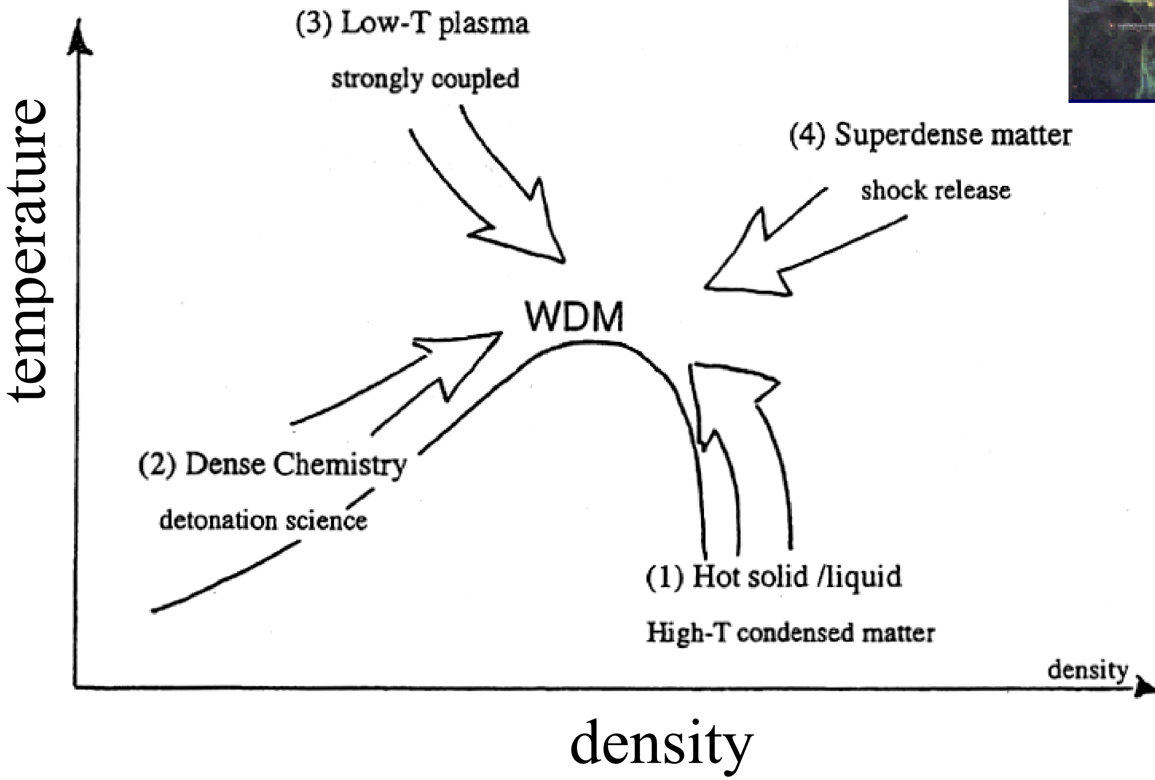
Planetary physics

Inertial fusion

Material science & engineering

Warm dense matter is at the meeting point of several distinct physical regimes - a scientifically rich area of High Energy Density Physics.

From R. More, Warm Dense Matter School, LBNL, Jan. 10-16, 2008. http://hifweb.lbl.gov/wdmschool/



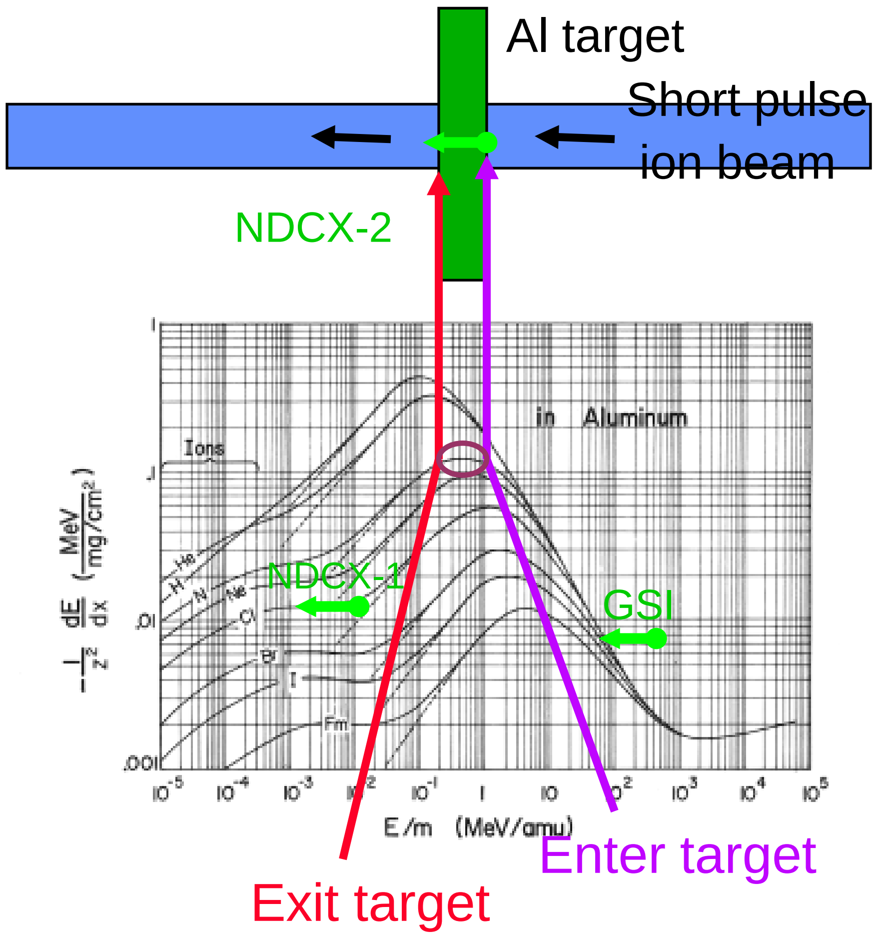
Unknown properties:
EOS (p(ρ,T), E(ρ,T))
Liquid-vapor boundary
Latent heat of evaporation
Evaporation rate
Surface tension
Work function
Electrical conductivity
dE/dX for hot targets

Phenomena:
Metal-insulator transition
Phase transitions?
Plasma composition?

Many properties in this regime are not well known.

Ion beams provide a tool for generating homogeneous warm dense matter.

- Warm dense matter (WDM)
  - T ~ 0.1 to 10 eV
  - ρ ~ 0.01 -1 * solid density
- Uniform energy deposition near flat portion of dE/dx curve, e.g. nuclear stopping plateau (NDCX-I); Bragg peak (NDCX-II)
- Other favorable characteristics include
  - Precise control of energy deposition
  - Large sample size ~micron depth, 1 mm diameter → easy to diagnose
  - Ability to heat any target material → broad industrial applications
  - Not sensitive to ‘bleaching’
  - Benign environment for diagnostics
  - Immune to blowoff plasma
  - High rep rate and reproducibility



L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970)

NDCX I is laying the groundwork for NDCX II.

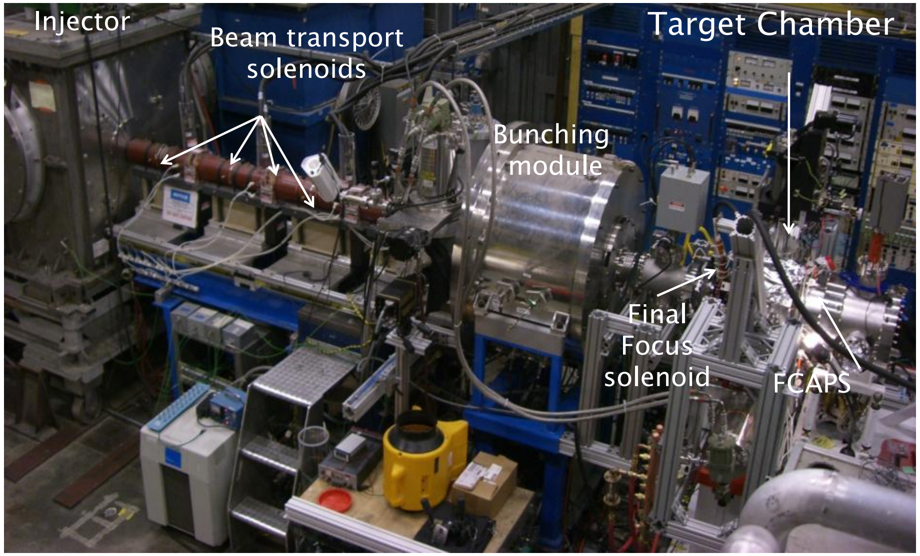
NDCX I

0.3 MeV,

0.01 μC

2 ns

Now



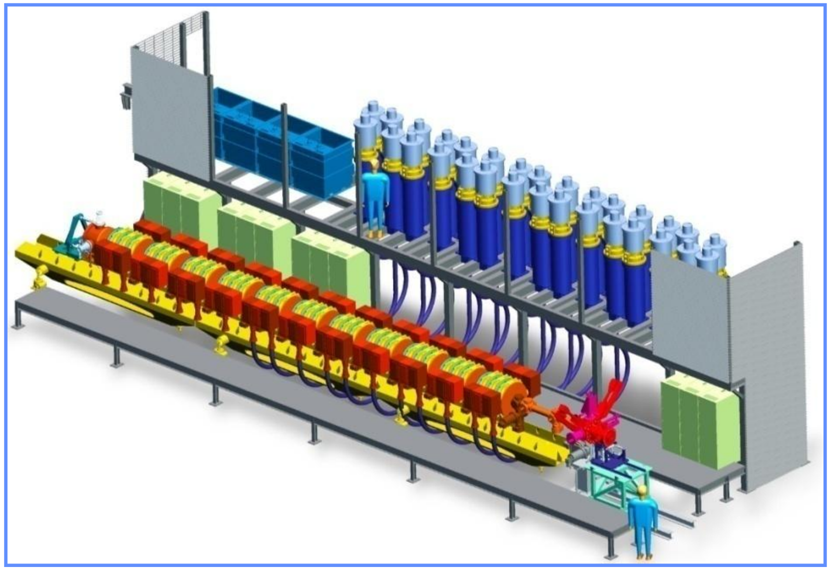
- Explore liquid/vapor boundaries at T ~ 0.4 eV
- Evaporation rates/ bubble and droplet formation
- Test beam compression physics
- Develop diagnostics

NDCX II

2 - 3 MeV, 0.03 μC

<1 ns

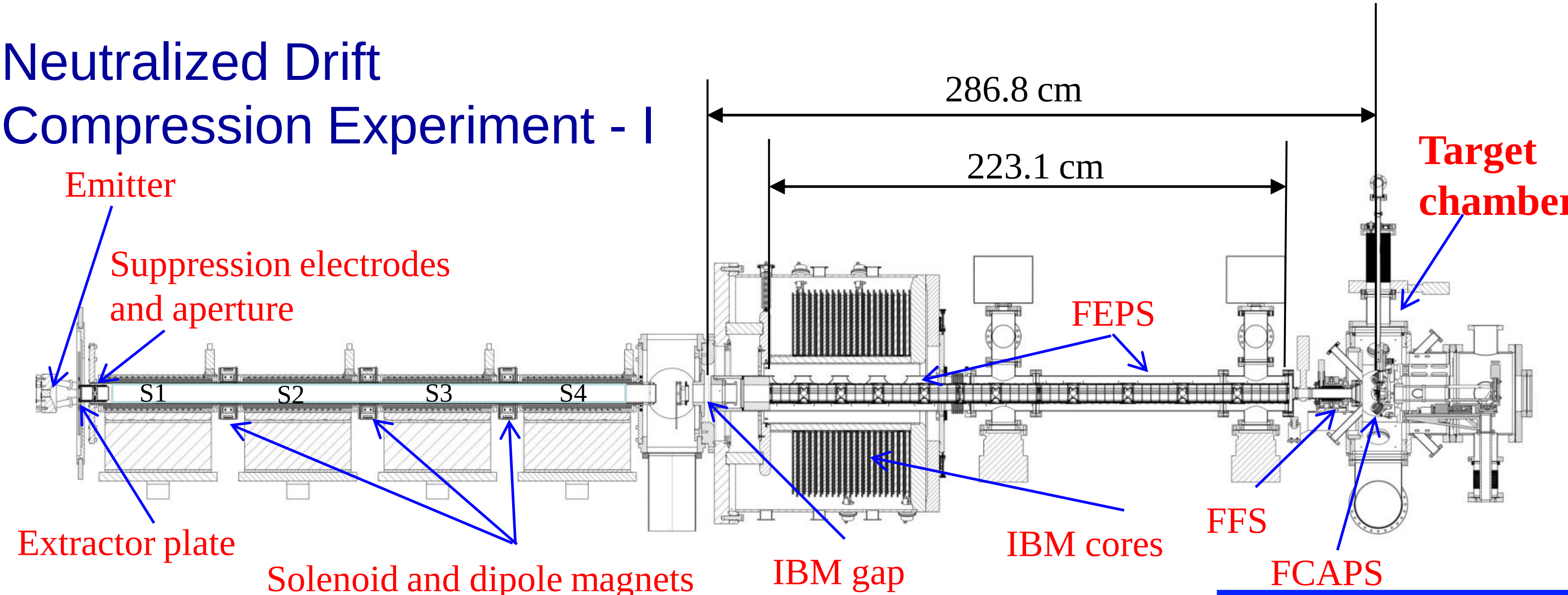
Completion date: 2012



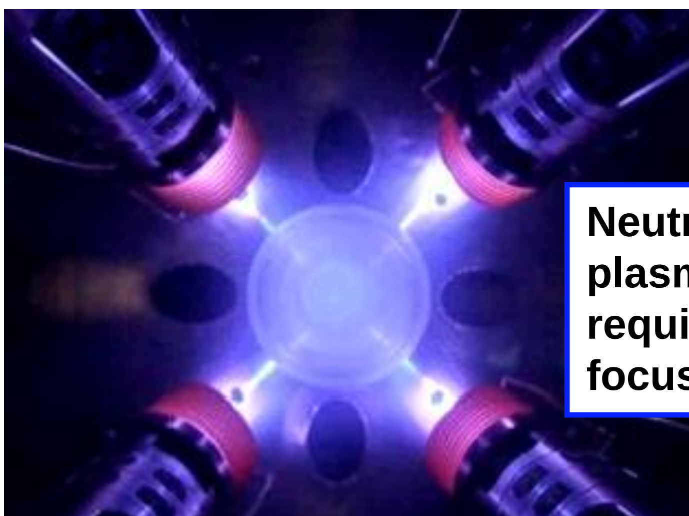
- Bragg peak heating
- T ~1-2 eV in planar targets
- Ion^+/Ion^- plasmas
- Critical point; complete liquid/ vapor boundary
- Transport physics
- HIF coupling and beam physics

NDCX-I has demonstrated factor ~100 pulse compression, with inductive bunching and plasma-based space charge neutralization.

Neutralized Drift Compression Experiment - I

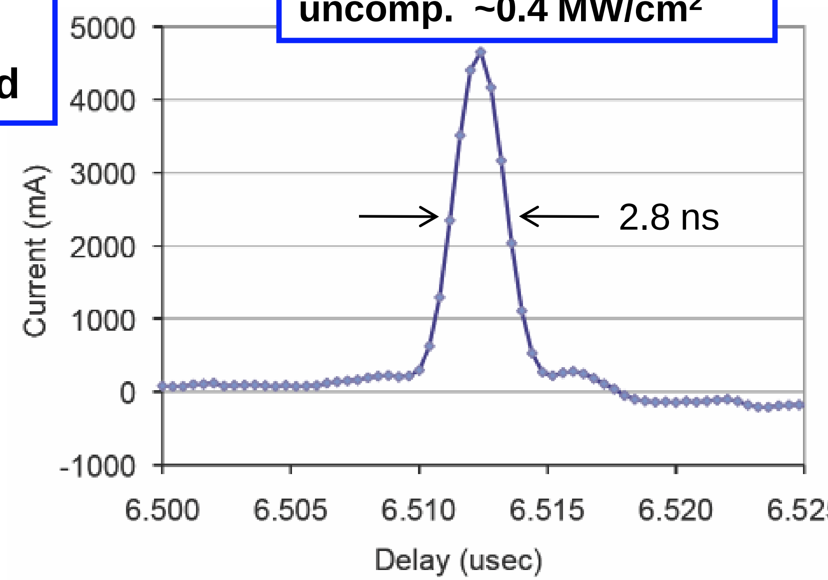


Velocity tilt accelerates tail, decelerates head

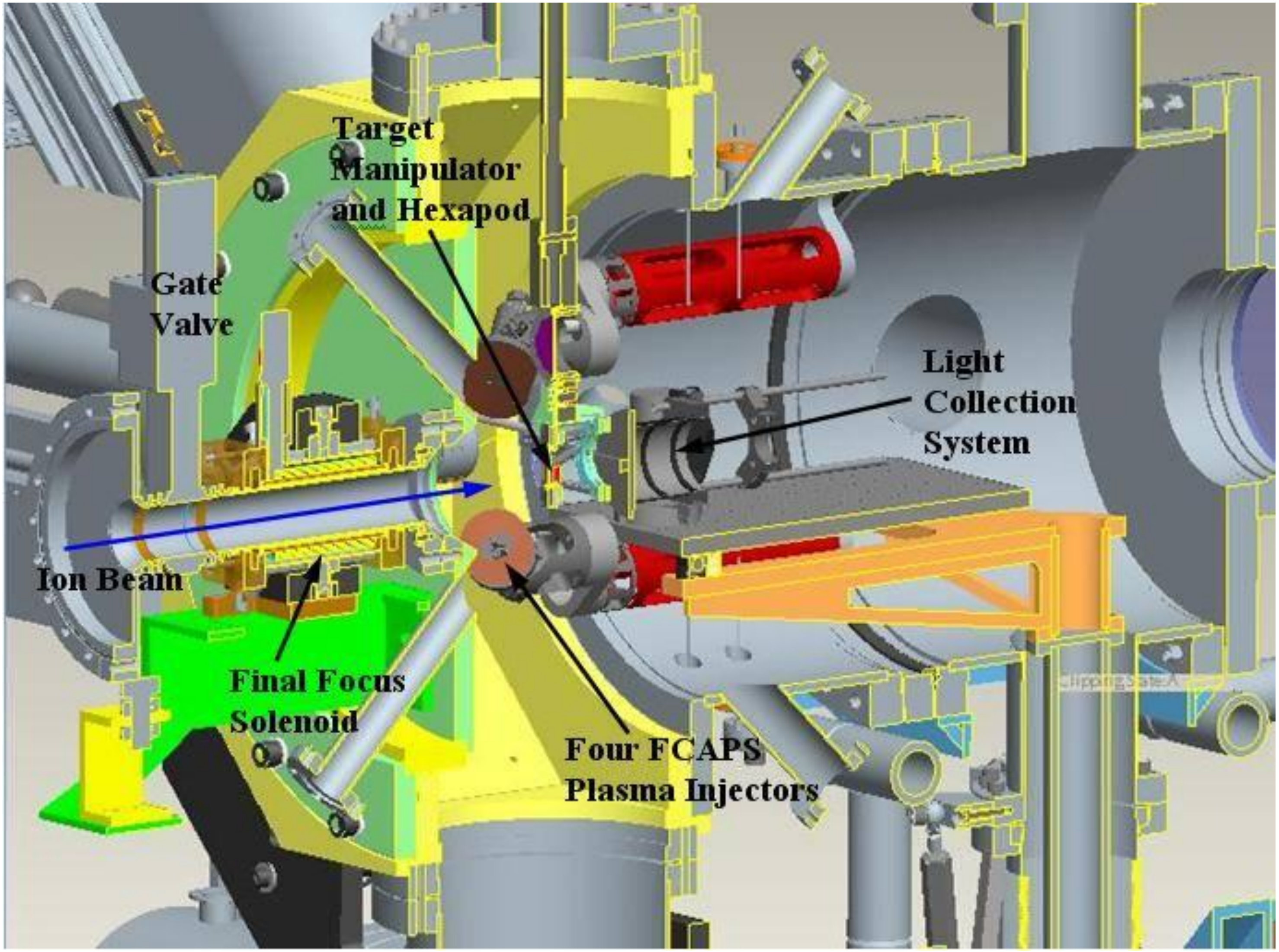


Neutralizing plasma is required for final focus

~4 mJ compressed pulse
uncomp. ~0.4 MW/cm^2



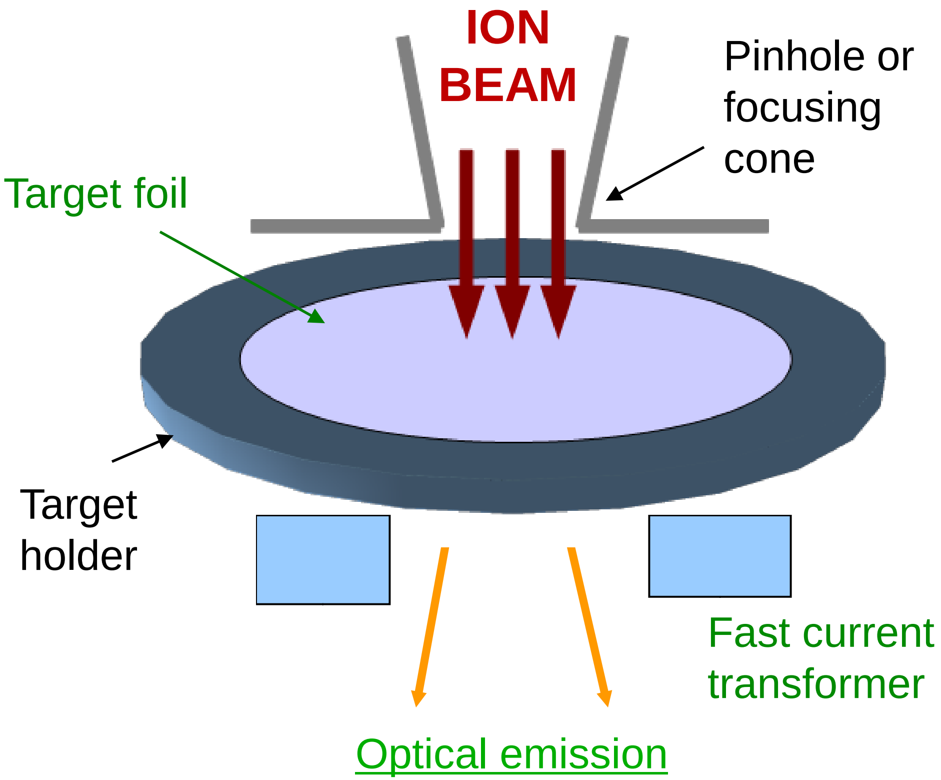
NDCX-I (0.3-MeV K^+) target chamber contains target, neutralizing plasma, and target diagnostics.



NDCX-I provides a test bed for target physics studies, target diagnostics development, and ion beam compression studies.

Diagnostics include

- Optical emission, especially high speed optical pyrometer
- High speed I-CCD cameras
- Streak camera
- Optical spectrometer
- Beam transmission
- Beam scattering
- Calorimeter foil target
- VISAR
- Laser backlighting/reflection/ polarimetry



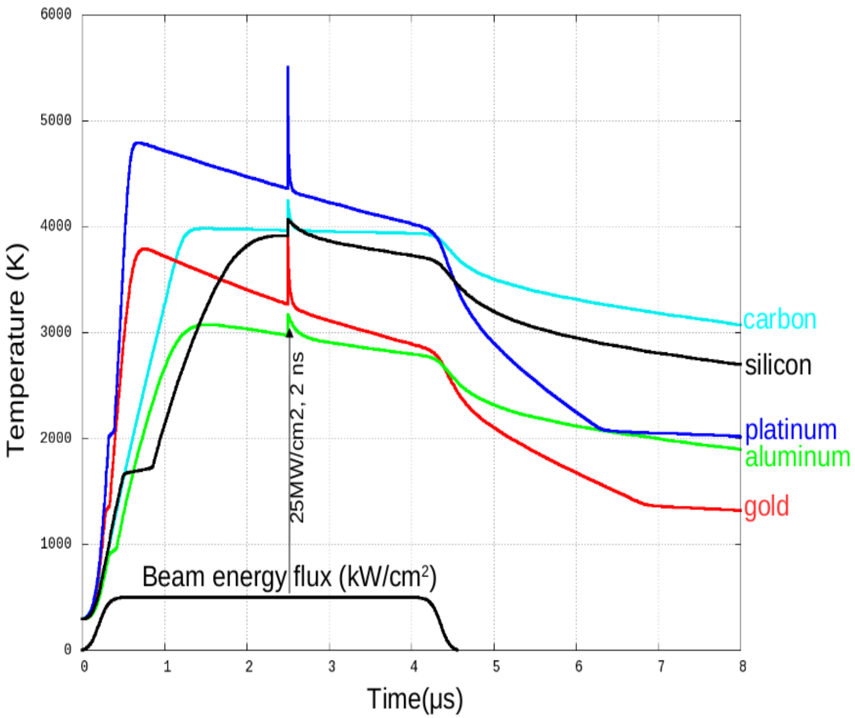
Targets tested on NDCX-I

Au (0.06, 0.15, 0.5 μm)

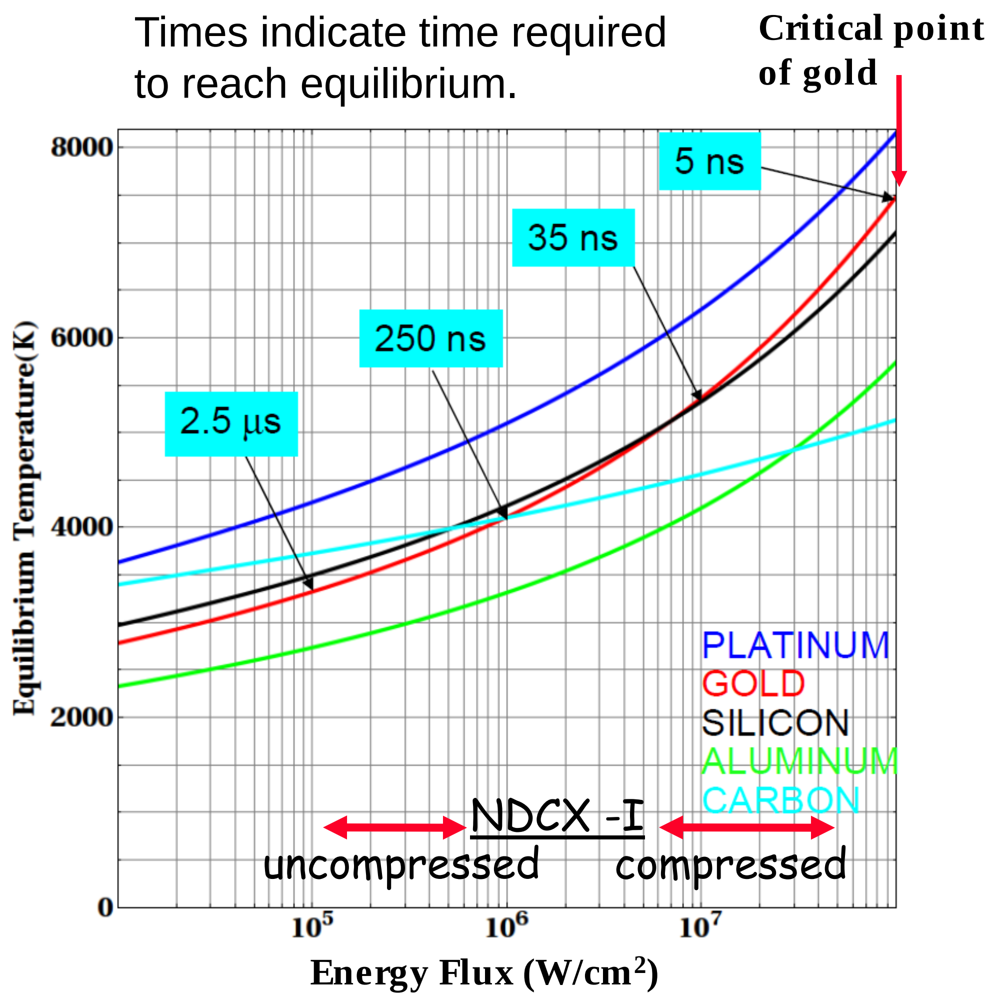
Pt (0.12 μm), W (3 μm)

Al, C, Si (0.4 μm)

Target heating models predict T ~ 0.3 – 0.5 eV using NDCX-I beam; T ~ 1 - 3 eV using NDCX-II beam.

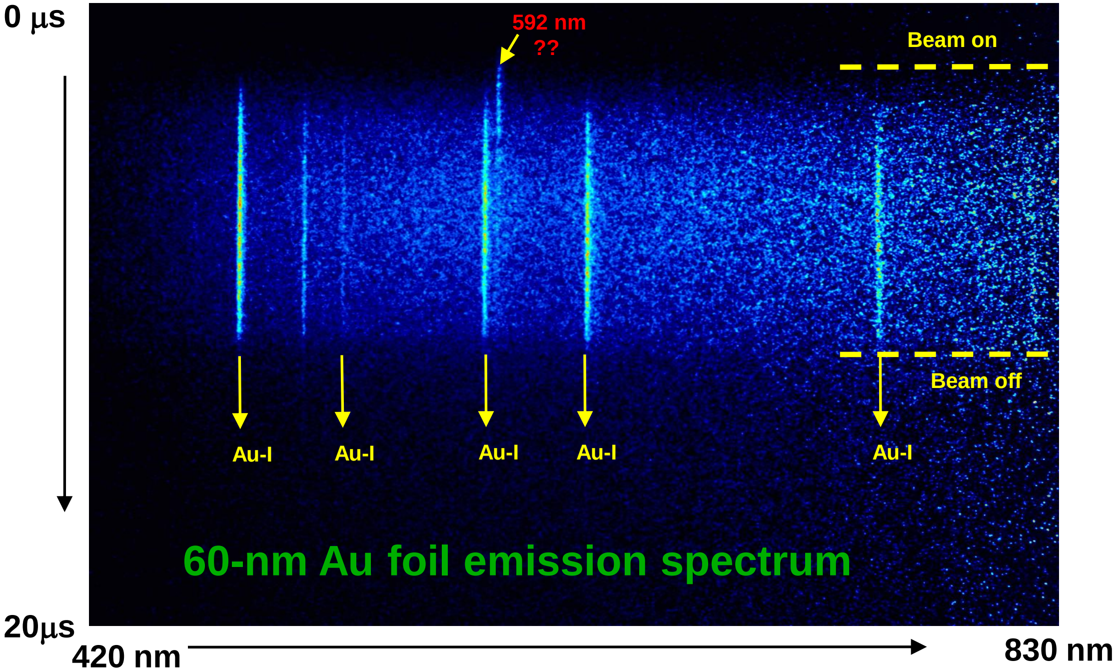


Times indicate time required to reach equilibrium.

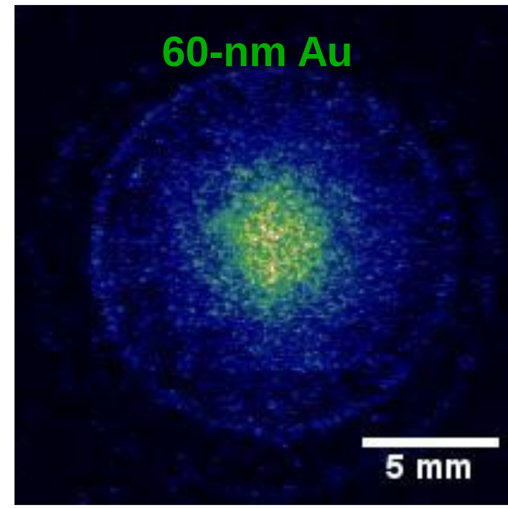


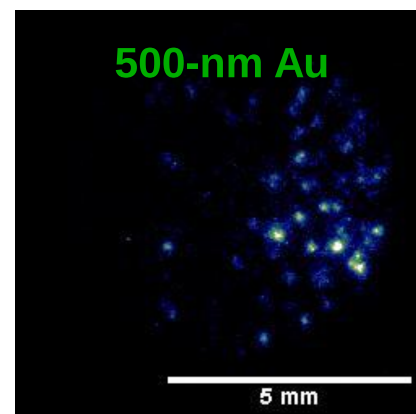
NDCX-II: power/unit area increased x 100-1000

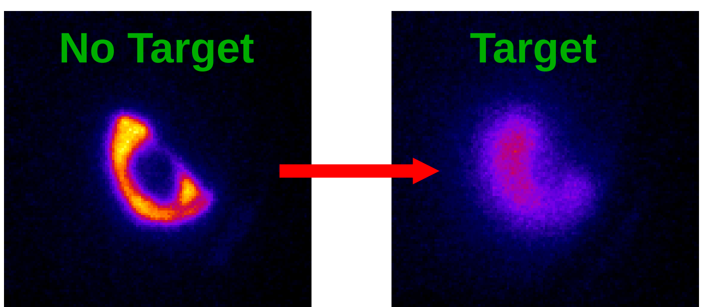
We are studying target behavior with optical and beam-based diagnostics.



Images of target debris at t = 500 µs.

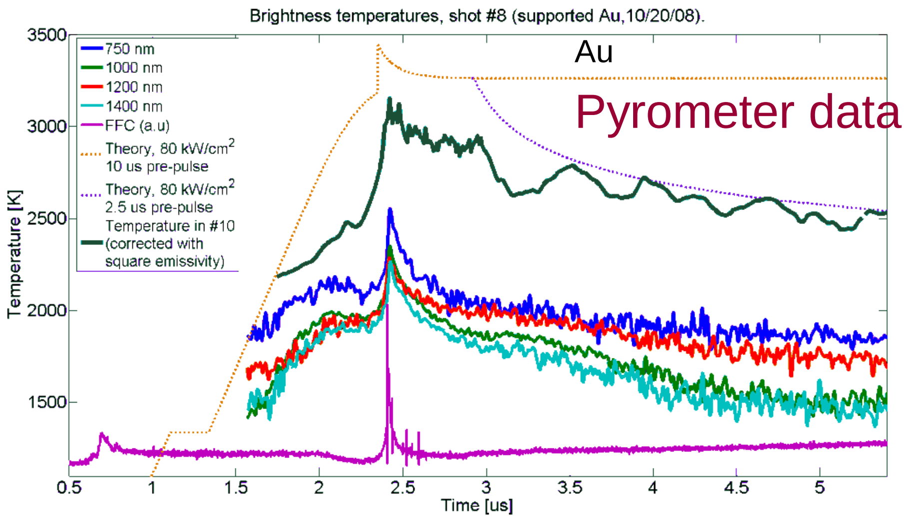


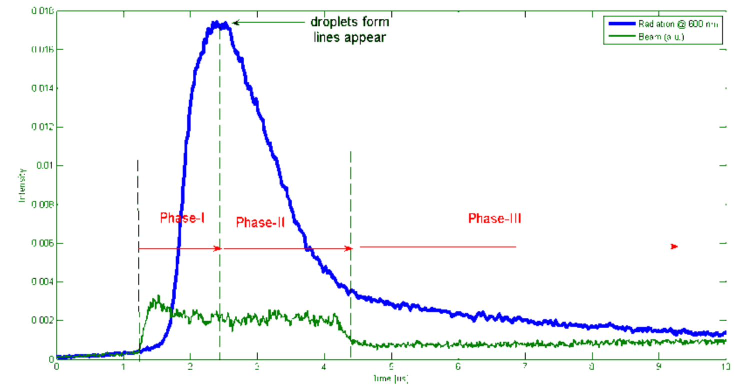




Scintillator image of beam scattering in target foil.

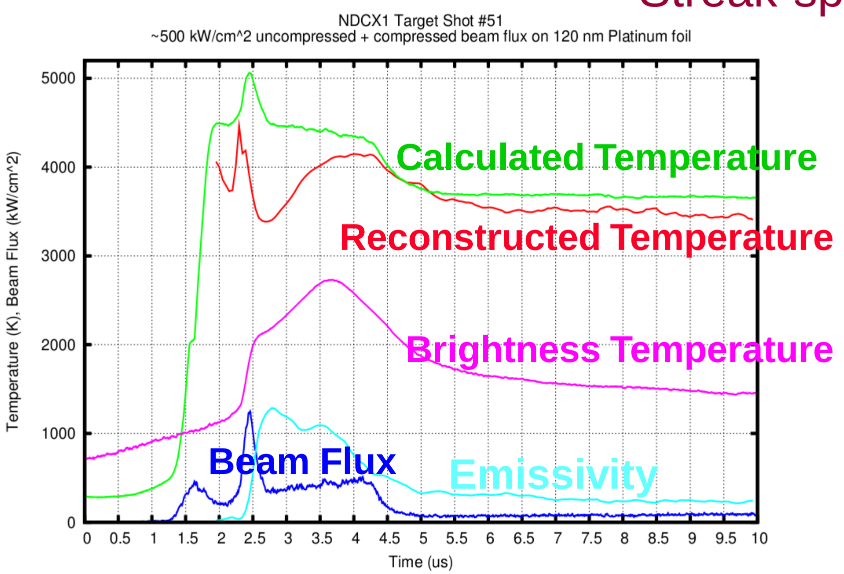
Initial pyrometer and streak spectrometer data indicate target temperature in range 3000-4500 K.

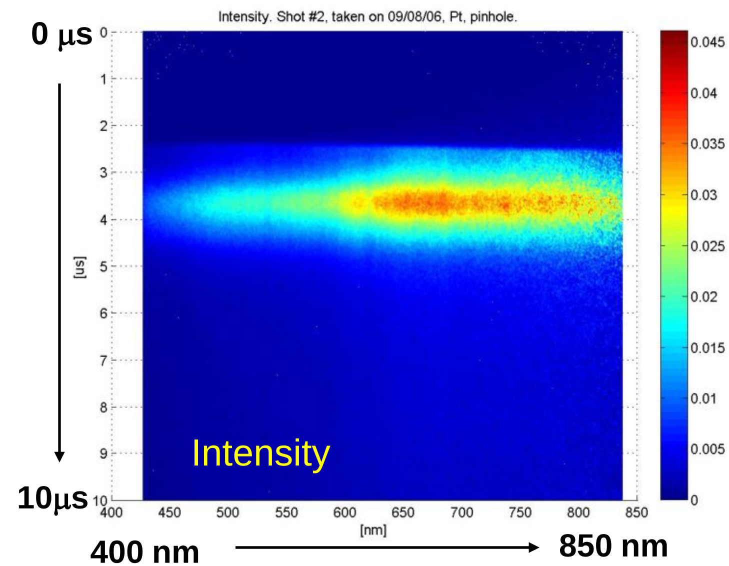




Thermal radiation at 600 nm and ion beam intensity

Streak-spectrometer data





Short to medium term plans for diagnostic development (Pavel Ni)

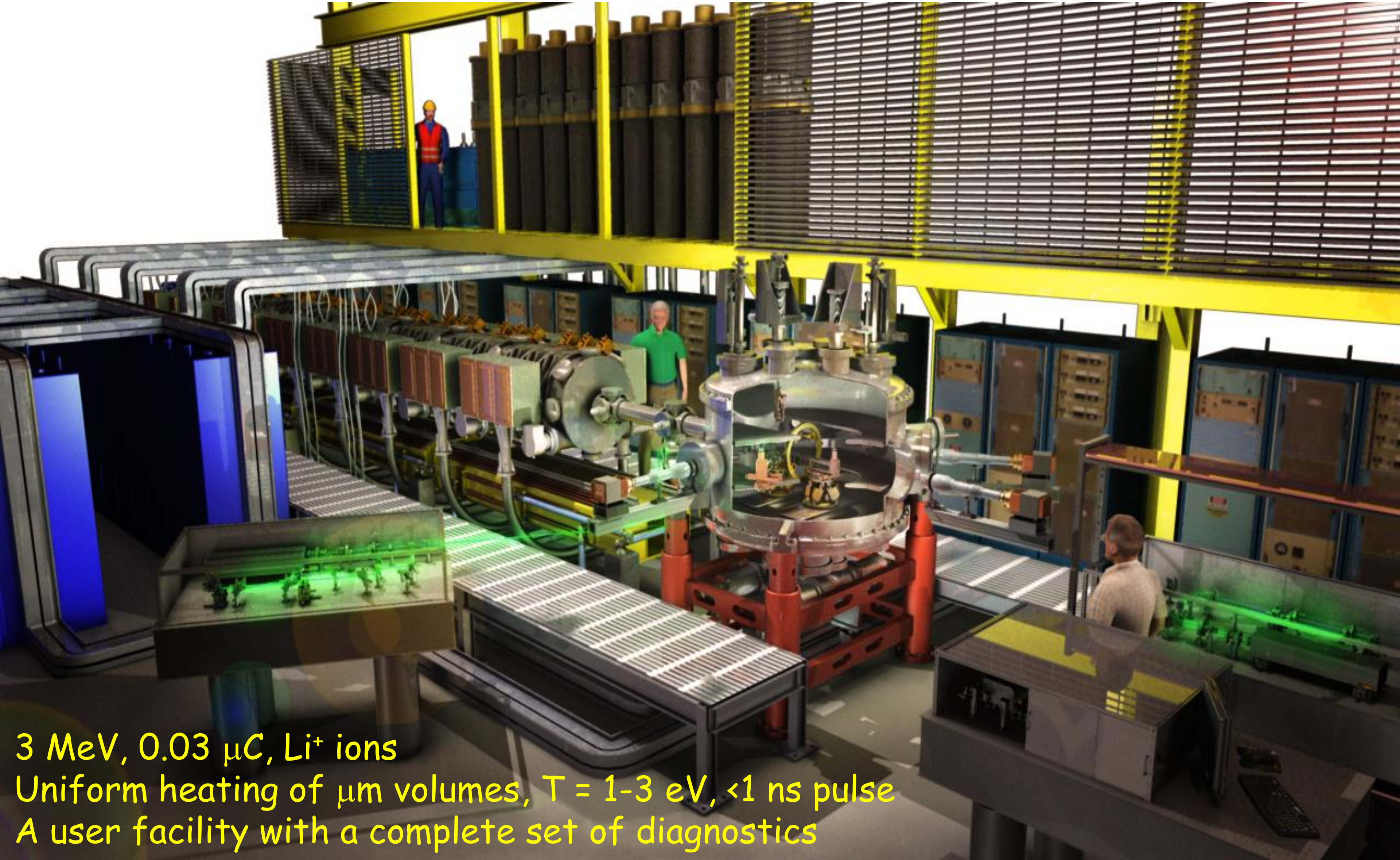
- Diagnostic development
  - Aerogel fragment catcher
  - Laser backlighting (target breakup)
  - VISAR (target expansion velocity)
  - Optical filters for camera to distinguish continuum, line radiation
  - Upgrades to accommodate higher temperature, finer spot size in NDCX-II
  - Gas jet for spectroscopic beam profile measurement
  - Energy analyzer downstream of target (dE/dx, charge state)
  - Polarization effects
  - Electrical conductivity
  - X-ray backlighting

NDCX-I provides a test bed for target physics studies, target diagnostics development, and ion beam compression studies.

Short to medium term target physics studies:

- Study droplet formation on ms time scale in liquid metals – droplet collection
- Stability of thick (150-500 nm) vs. thin (60-nm) Au targets
- 2-3 micron tungsten foil: solid-liquid transition and calorimeter
- Study response of target to optimized compressed pulse
- Final focus cone study and optimization
- Transient darkening, changes in optical properties (metal-insulator, other phase transitions)
- Aerogel target: effect of porous materials, transient darkening
- Fragmentation/fracture mechanics of materials under extreme conditions (e.g. carbon, silicon)
- Beam scattering, charge state, dE/dx in WDM targets
- Target conductivity, evaporation rate, …
- Develop tamper concepts to increase target temperature
- Positive/negative ion halogen target (possibly Au, Pt if T > 0.4 eV): requires development of 100-150 nm UV diagnostics
- Explore applications, e.g. backlighting, droplets…

NDCX-II Warm Dense Matter Research Facility is under construction (completion 2012).



Plans for WDM experiments on NDCX-II

- NDCX-II should increase beam intensity on target by factor >100x (~$10^{9\text{-}10}$ W/cm^3). Increased intensity and longer range should increase possibilities for experimental study. Possible experiments include:

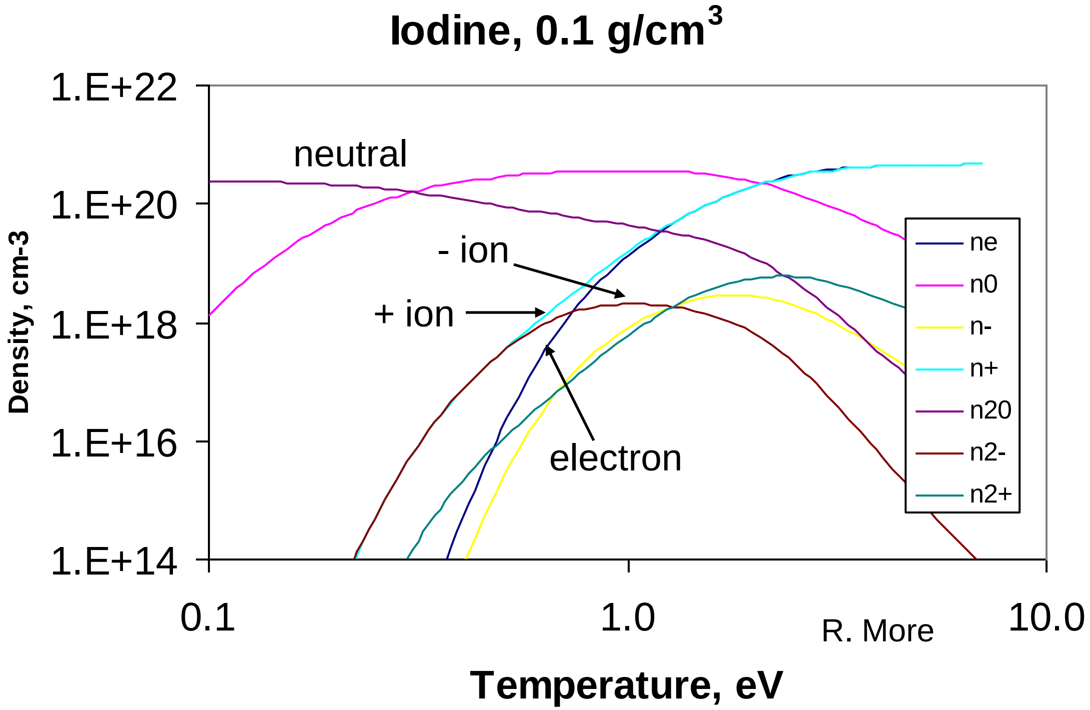
- Continue experiments from NDCX-I
- Phase transitions, esp. liquid-gas interface, critical point
- Porous targets
- High field final focus solenoid
- Positive/negative ion targets
- Mapping critical density surface using multi-wavelength optical probe
- Shock wave studies related to IFE applications
- Shock physics related to WDM
- Ion beam dynamics (focusing, neutralization)
- Cylindrical/spherical bubble implosions

NDCX II can generate high electron affinity WDM dominated by +/- ions.

Electron affinity:

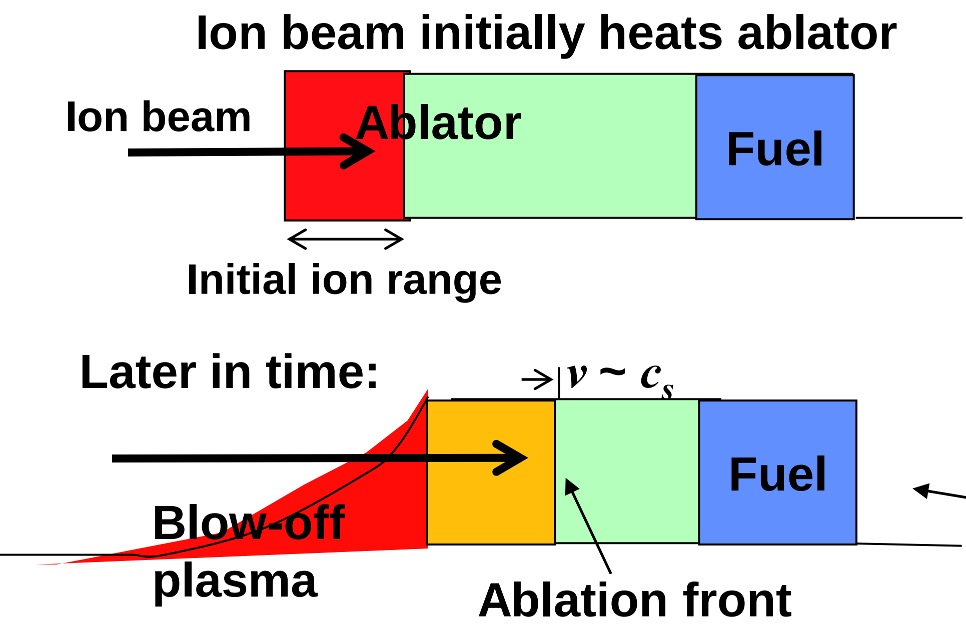
Br	3.4	eV
I	3.1	
Au	2.3	
Pt	2.1	

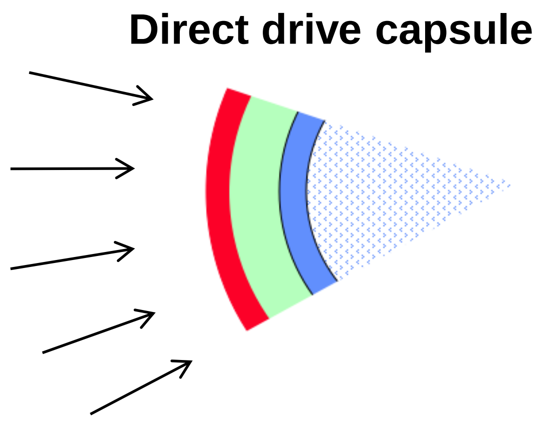
H Yoneda, et al., Phys. Rev. Lett. 2003, 91, 75004.



- Explore behavior of material with unusual properties
- Narrow temperature range; e.g. 0.4 to 0.7 eV for iodine at 0.1 g/cc.
- Expect characteristic charge exchange line radiation in EUV ~100-150 nm
- Expect conduction by charge transfer – measure electrical conductivity
- Other: optical behavior, metal-insulator transition

Direct-drive coupling experiment can be performed on NDCX-II by ramping beam energy.





Ramp beam energy to position peak energy deposition to follow shock front => Potentially high coupling efficiency.

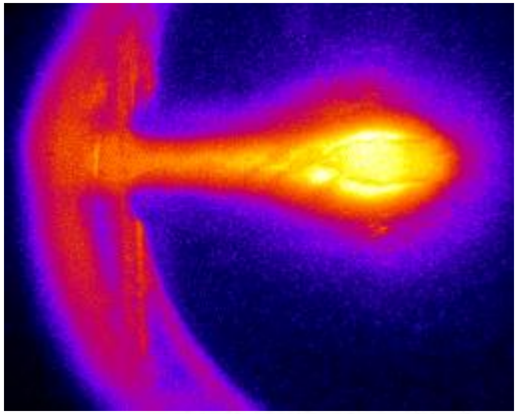
Perform experiment by placing target upstream of longitudinal focus to optimize energy ramp.

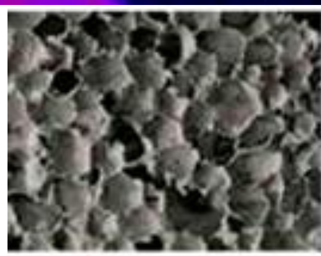
- Diagnostics include VISAR to measure shock strength at downstream surface of the target
- Possible transparent target (cryo frozen argon), with dopant layer to light up as shock wave passes through.

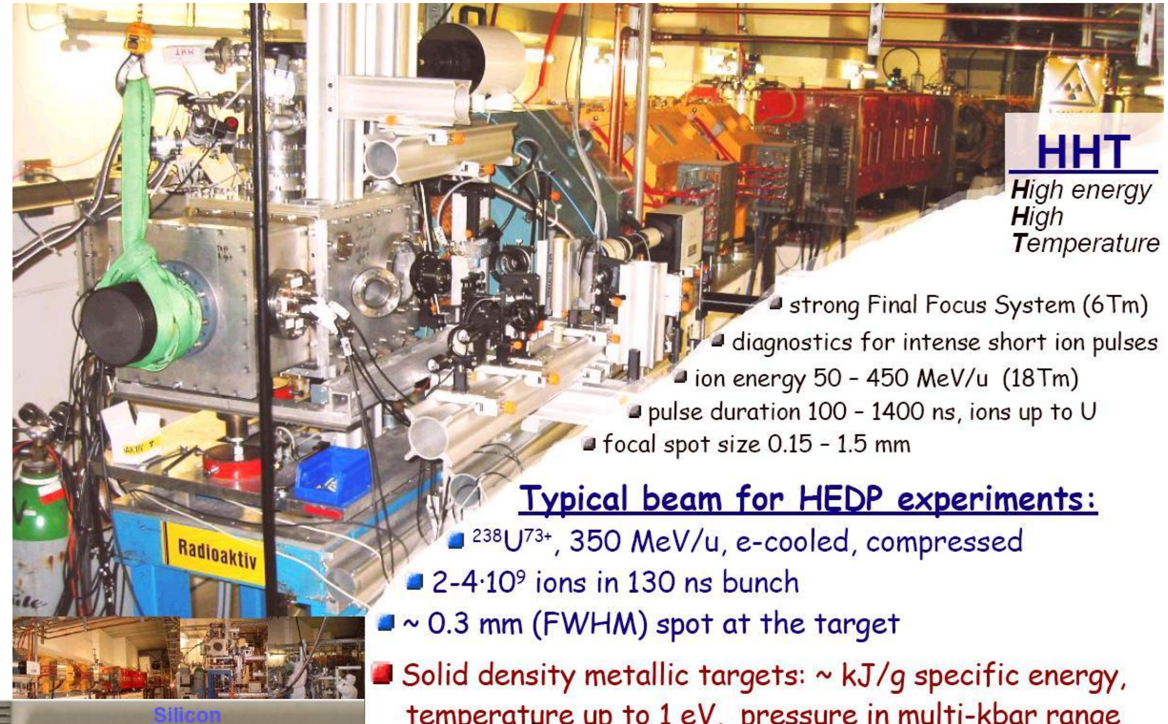
Longer-term diagnostic and target station development (NDCX-II, IB-HEDPX).

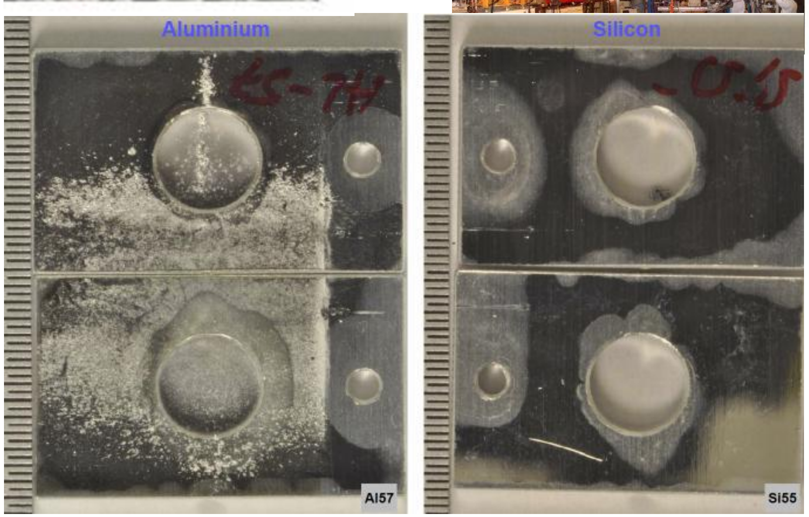
- Cryo-target capability
- X-ray diagnostics
- Thomson scattering
- Beam and accelerator diagnostics
- Laser-based diagnostics
- High-power pulsed laser systems, e.g. driving shocks

Experiments at GSI include porous target experiments and target holder fragmentation experiment.









Summary

- NDCX-I provides a test bed for target physics studies, target diagnostics development, and ion beam compression studies.
- Future experiments with NDCX-I and NDCX-II will explore aspects of WDM physics including beam manipulation, high electron affinity targets, beam-target coupling, etc.
- We need input from NDCX user community to increase productivity of the facility, including development of new diagnostics.

Some suggested questions for WDM experiments and theory group

- We need input from NDCX user community to increase productivity of the facility, including development of new diagnostics.
  - What are the main experimental objective of all WDM facilities?
  - What is the range of temperature and density that encompasses the objectives?
  - What are the experiments to address the objectives?
  - What are the theory needs for the experiments?
  - What are the theories that will be tested?
  - Can equations of state by built that have fundamental parameters than can be tuned by the experiments?
  - How will droplets and surface tension effects be addressed at ion facilities?

NDCX-II vs. NDCX-I

	NDCX-I (typical bunched beam)	NDCX-II 15-cell (r,z simulation)	NDCX-II 22-cell (r,z simulation)
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)
Total charge	15 nC	55 nC	55 nC
Ion kinetic energy	0.3 MeV	2.0 MeV	3.5 MeV
Focal radius (containing 50% of beam)	2 mm	0.7 mm	0.55 mm
Bunch duration (FWHM)	2 ns	0.45 ns	0.45 ns
Peak current	3 A	17 A	37 A
Peak fluence (time integrated)	0.03 J/cm^2	17 J/cm^2	32 J/cm^2
Fluence within a 0.1 mm diameter spot	0.03 J/cm^2 (50 ns window)	9.5 J/cm^2 (1 ns window)	22 J/cm^2 (1 ns window)
Fluence within 50% focal radius and FWHM duration (k.e. x I x t / area)	0.014 J/cm^2	1.0 J/cm^2	6.1 J/cm^2

These estimates are from (r,z) Warp runs (no misalignments), and assume no timing or voltage jitter in acceleration pulses, no jitter in solenoid excitation, perfect neutralization, and a uniform non-depleted source; they also assume no fine energy correction (e.g., tuning the final tilt waveforms) [Alex Friedman]